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CTS/COMSTAR

COMMUNICATIONS LINK CHARACTERIZATION

EXPERIMENT

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This Final Report summarizes the research conducted under Contract NAS 5-22575 between the NASA Goddard Space Flight Center and The Ohio State University Research Foundation. This effort covered the time period from September 2, 1975 to March 31, 1980. The objectives of the various research tasks conducted are identified and the methods of accomplishing these objectives are described. References to the technical reports, presentations, and papers containing the detailed technical results of these efforts are presented.		

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OBJECTIVES AND INTRODUCTION

The primary objective of this effort has been the measurement of angle of arrival and amplitude fluctuations on millimeter wavelength earth-space communication links. These characteristics are of considerable importance since they influence the design of such links and ultimately establish limits to the reliability of such links. Subsidiary objectives have included the measurement of rainfall attenuation and radiometric temperature statistics and the assessment of the performance of a self-phased array as a receive antenna on an earth-space link.

These objectives have been accomplished through the implementation and execution of four related but distinct experiments; these four experiments are the CTS angle of arrival experiment, the ATS-6 return experiment, the Comstar angle of arrival experiment, and the gain degradation experiment. These experiments are described in the following. Key results are summarized and references are given for more detailed presentation of both the experiment and results.

Also included in the following are references to related publications and activities generated as a consequence of this research effort.

CTS ANGLE OF ARRIVAL EXPERIMENT

A wave traveling through the atmosphere will suffer phase perturbations as a result of index of refraction fluctuations caused by turbulence. In its simplest form this effect may be considered to be a local tilting of the phase front of a uniform plane wave. Expressed in an alternative manner, the ray path from the source to the receiver is perturbed such that the direction from which it arrives at the receiver fluctuates with time. In the more general interpretation, energy will be removed from the incident plane wave and converted into a spatial-temporal spectrum of plane waves. The signal arriving at the receiver will then consist of a wave whose phase front is randomly

fluctuating both in space and in time. In addition to this phase phenomenon, of course, there will be amplitude fluctuations caused by the alternate "focusing and defocusing" of the signal as it passes through the turbulence. It must be understood that both of these phenomena are properties of the wave traveling through a turbulent medium and, hence, are independent of the characteristics of the receiving aperture. Thus, it remains to establish the behavior of the receiving aperture when illuminated by such a signal.

The antenna gain customarily used in system margin design calculations is defined in terms of the antenna's behavior when illuminated by a uniform plane wave. Therefore, if the phase perturbations described above are significant, a resulting loss of gain, i.e., gain degradation, can occur. This loss may be interpreted, as before, in two different ways. First, if one thinks simply in terms of angle of arrival fluctuations, the incident signal will arrive from directions different than the maximum gain direction for a certain percentage of time; hence, the average gain will be lower than anticipated. Alternatively, using the more general interpretation, the various ray paths which reflect from small surface elements of the parabolic reflecting surface and subsequently sum at the feed point will no longer all have the same phase. Thus, the total power available at the feed point will be reduced.

Although these properties of the turbulent atmosphere and their consequences with regard to aperture antennas are well understood in general, the magnitude of these effects and the probabilities of their occurrence at millimeter wavelengths have not been available to the design engineer. It is clear from elementary considerations that the resulting effects increase with increasing electrical size of the receiving aperture, i.e., both the operating frequency and the physical size of the aperture, and with increasing path length in the sensible atmosphere.

It is also known that the extent of these phenomena increases with increasing atmospheric turbulence. However, almost nothing is

known about integrated path effects of turbulence for paths through attenuating rain events. Although the state of atmospheric turbulence as measured by the structure constant can vary by as much as two orders of magnitude on a day-to-day basis, very little is known about this parameter in the presence of convective rain cells. Intuitively, one would expect that turbulent effects would be enhanced during such events. Unfortunately, these deleterious effects would then compound the widely examined problem of rain attenuation.

The availability of the 24 hour/day, 11.7 GHz beacon on the Communications Technology Satellite (CTS) provided the first opportunity for the statistical measurement of these characteristics. This geosynchronous satellite was visible from the OSU Satellite Communication Facility at an elevation angle of 32° . Therefore, a four element, self-phased array was implemented for reception of this beacon signal. 60 cm focal point feed parabolic antennas were used for the elements of this array. These elements were placed at the corners of a 1 m square, planar array oriented such that the plane of the array was perpendicular to the nominal propagation path. Within this plane, the square array was oriented such that the top and bottom of the square array were parallel to the local horizontal.

The receiving system consisted of four second order phase lock loop (PLL) receivers. The outer PLL removed all long term slowly varying phase fluctuations common to all elements; these fluctuations were a result of the diurnal motion of the satellite along the propagation path, i.e., Doppler shift. The inner PLL's then compensated for the diurnal motion of the satellite in the plane perpendicular to the propagation path, i.e., pointing direction. Thus, the array was self-tracking and required no mechanical repositioning to follow the diurnal motion of the satellite. The 60 cm element aperture size was selected so that this diurnal motion caused a minimal variation in the fixed element received signal level. Antenna gain was then achieved by the coherent summing of the phase aligned signals from the four elements.

Four phase detectors were also implemented to measure the phase differences between adjacent array elements. Thus, the relative phase differences between two spaced pairs of elements in both the azimuth and elevation planes were obtained. Interpreted in the simplest manner, one pair of these phase differences, i.e., a phase difference in the elevation plane and a phase difference in the azimuth plane, is sufficient to determine the angle of arrival of an ideal uniform plane wave. Alternatively, interpreting the results in a more general manner, the phase at three points in space may be sampled relative to the fourth element. This interpretation is obviously appropriate to the case of an incident plane wave spectrum where the angle of arrival may not be well defined. The details of the measurement and initial results are presented in References 5, 8, and 10.

The self phased array is also of interest in itself. It offers two distinct advantages as a receive terminal antenna. First, it requires no mechanical repositioning to follow the diurnal motion of the satellite regardless of the desired antenna gain. And, second, it provides a method of overcoming angle of arrival gain degradation which might be experienced by a larger single aperture. The economic trade-off for this approach revolves primarily around the absence of the need for mechanical positioning versus the cost of multiple front-ends. The optimization of self-phased arrays for this application is considered in References 12 and 13.

This experiment was implemented in early 1976 and the CTS beacon was acquired on February 20, 1976. With the exception of the ATS-6 return period as noted below, this experiment operated virtually continuously until June 1, 1978. The numbers of hours of data per month recorded during this period are summarized in Table 1.

Small, virtually instantaneous discrete frequency steps were first observed on the beacon signal during December, 1976. Some of these steps, as large as 40 Hz, caused loss of lock in the receiving system. By January, 1977, much larger frequency excursions were

TABLE 1.

Summary of CTS angle of arrival data periods.

<u>Month</u>	<u>Hours of Data</u>
May, 1976	373
June	554
July	223 ¹
August	474 ²
September	--- ²
October	--- ²
November	--- ³
December	416
January, 1977	526 ⁴
February	481
March	423
April	570
May	514
June	648
July	417
August	249 ⁵
September	403
October	500
November	625
December	572
January, 1978	626
February	270 ⁶
March	487
April	552
May	657
TOTAL	10,559

¹Data system tape failure and system modification.²ATS-6 return period 8/27/76 to 10/26/76.³Receiver failure.⁴Commencement of large frequency excursions.⁵Air conditioner failure.⁶Coal shortage.

observed; these excursions were as large as 1,200 Hz within a 30 minute period in addition to the usual Doppler shift. Measurements made by the Communications Research Centre, Ottawa, confirmed that these frequency shifts were indeed originating within the satellite beacon rather than the OSU receiving system.

In order to reduce the amount of data lost due to these sporadic events, a new reacquisition system was incorporated in March, 1977. The receiver bandwidth of 80 Hz could have been increased to compensate for some of the smaller excursions; however, this approach would have led to an unacceptable degradation in the overall quality of the phase data. Some loss of data quality was also experienced with the approach chosen but not as much as would have occurred with increased bandwidth. During the remainder of the experiments these excursions became worse during eclipse periods and improved following eclipse periods.

Figures 1, 2, and 3 are examples of the data resulting from this experiment. Figure 1 shows a typical rain fade event occurring on Day 193, 1977. This 15 dB fade was accompanied by phase differences as large as 140° . This electrical phase difference would correspond to an angle of arrival fluctuation on the order of 0.5° .

Figure 2 shows fade distributions for the entire data period. These appear to be quite consistent over the course of the experiment.

Finally, Figure 3 shows the distribution of phase differences for a typical month (May, 1978). It should be noted that a phase difference of 30° is exceeded 0.01% of the time. This electrical phase difference corresponds to an angle of arrival deviation of 0.12° . It will be shown below that this angle of arrival deviation is consistent with those observed at 28.56 GHz using the Comstar D/3 beacon.

It should also be noted that, if this angle of arrival deviation were interpreted simply as a tilt in the phase front of a uniform plane wave, it would certainly cause gain degradation for reasonable size

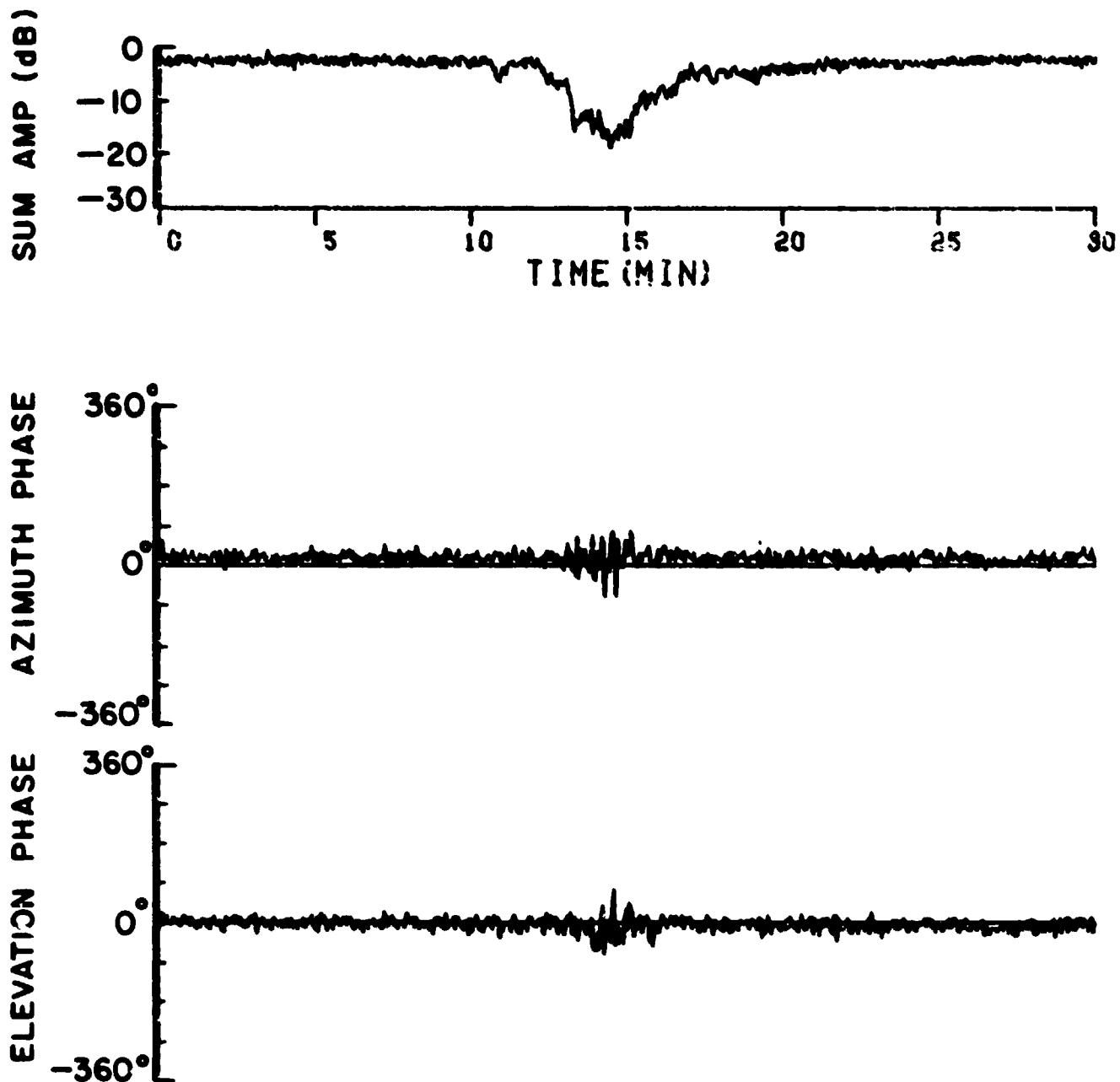


Figure 1. Array sum amplitude and differential phases. CTS 11.7 GHz beacon. Day 193, Hour 21, Minute 58, Second 58, 1977.

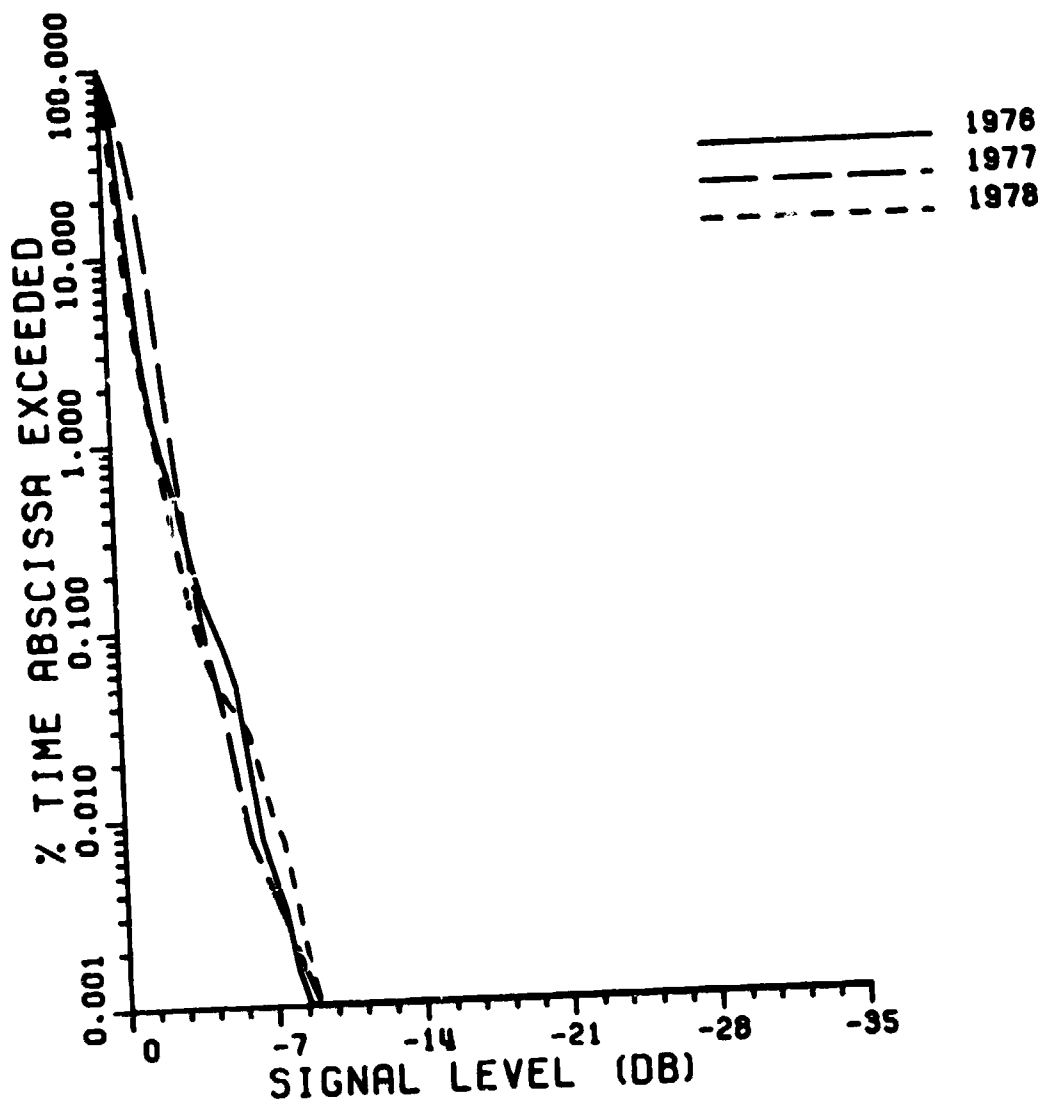


Figure 2. 11.7 GHz fade distributions.

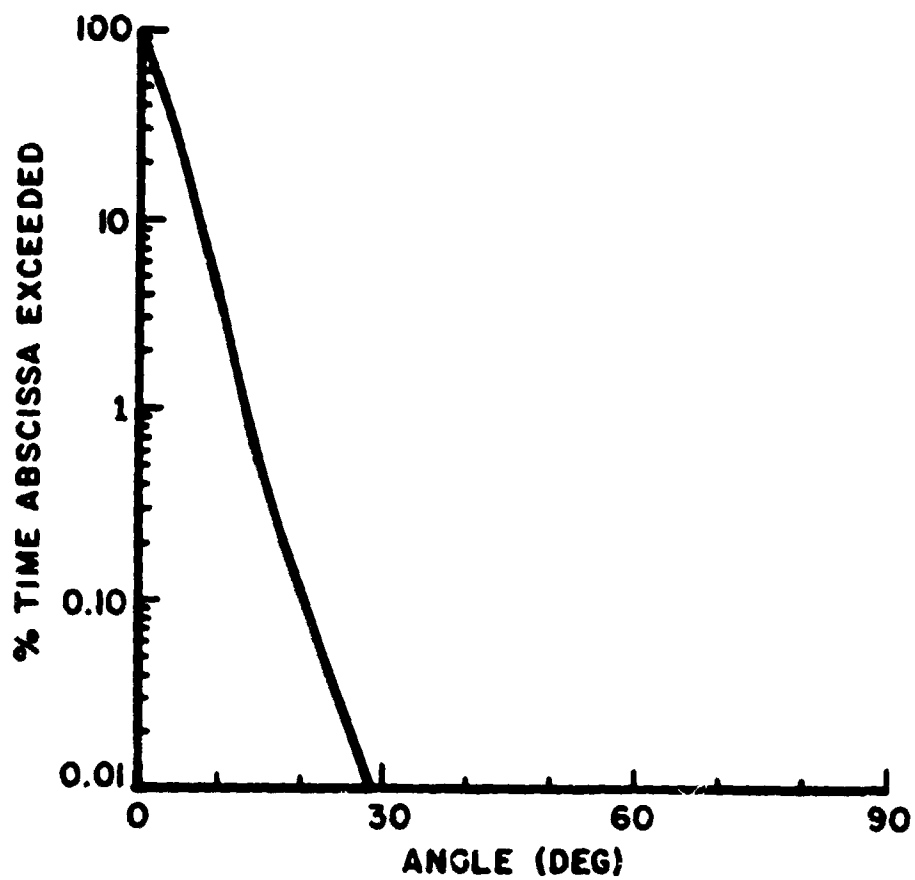


Figure 3. Average distribution of phase differences for May, 1978.

antennas. For example, a 10 meter parabolic antenna operating at 11.7 GHz would have a beamwidth of about 0.21° ; therefore, an angle of arrival deviation of 0.21° would cause a gain degradation of more than 3 dB. This gain degradation would be in addition to any attenuation loss experienced on the propagation path.

The results of the CTS angle of arrival experiment are presented in detail in Reference 11.

ATS-6 RETURN EXPERIMENT

During the Fall of 1976 the ATS-6 geosynchronous satellite was permitted to drift from its position over the Indian Ocean back to a position over the U.S. This movement provided an extraordinary opportunity to examine amplitude scintillation as a function of elevation angle during this movement. Therefore, during this period the CTS angle of arrival experiment was temporarily interrupted and the experimental facilities were diverted to the ATS-6 scintillation measurements.

Beacon receivers were implemented at the OSU Satellite Communication Facility for reception of the 360 MHz, 2.075 GHz, 20 GHz, and 30 GHz beacon signals. 10 m parabolic antennas were used for the two lower frequencies and a 5 m parabolic antenna was shared for the two higher frequencies.

Unfortunately, the 20 GHz beacon on ATS-6 failed prior to the experiment; and, the 360 MHz signal was badly contaminated by interference at the OSU terminal. Nevertheless, an extremely useful 84 hour data set was obtained at 2.075 and 30 GHz for elevation angles from 0.4 to 43.9° . The margins for the 2.075 and 30 GHz measurements were 50 and 60 dB, respectively. The ATS-6 beacons were acquired on August 29, 1976, and measurements continued until mid-October, 1976.

The variances of both of the received signals were found to agree well with those predicted by the Kolmogorov turbulence model, i.e., the

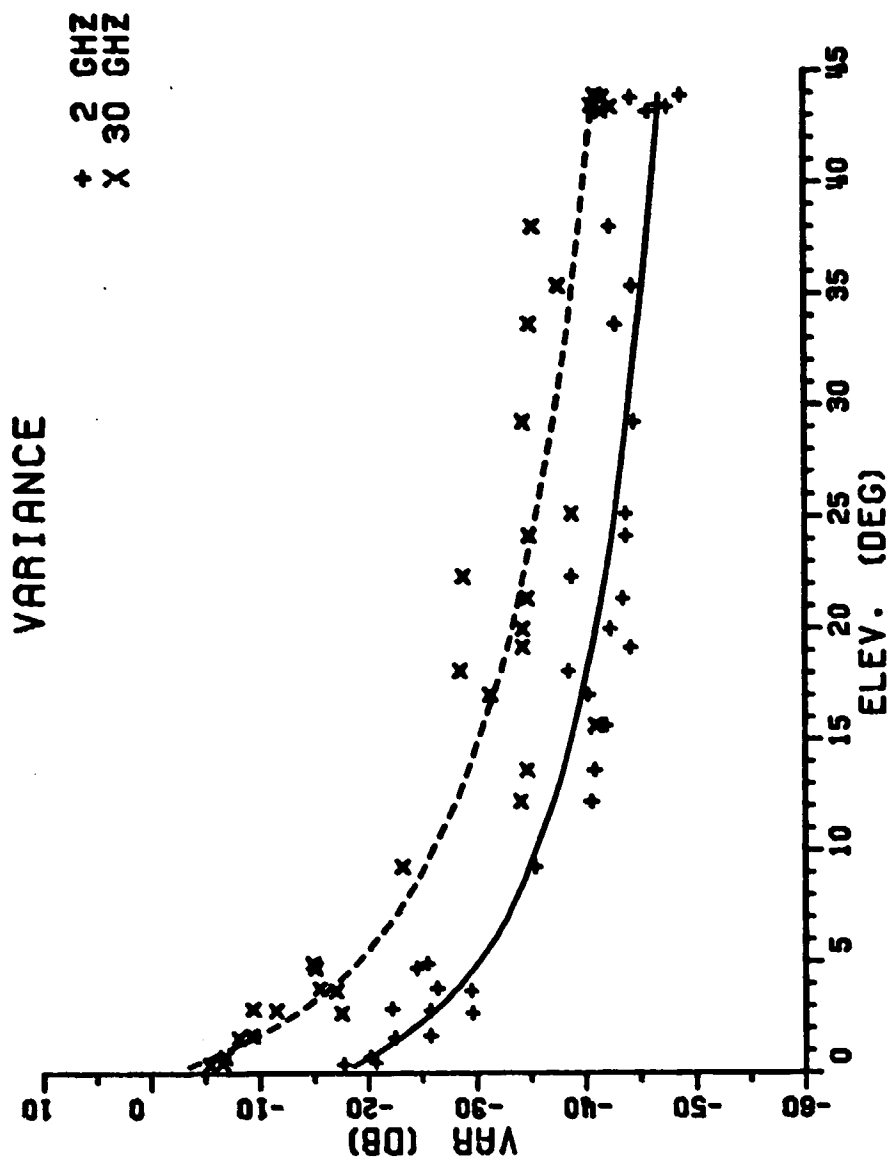


Figure 4. Mean amplitude variance with elevation angle. Spherical earth model.

variances were proportional to the $11/6$ power of the path length. It was also found that a uniform spherical atmosphere of about 6 Km height provided an adequate model for the prediction of this variance behavior. Plots of the measured variances and the model results are shown in Figure 4.

The cross correlations agreed well with Lee and Harp's predictions in general but tended to smaller values for lower elevation angles, i.e., longer path lengths through the sensible atmosphere.

The mean received power was also observed to fall off sharply at very low elevation angles. This effect could not be explained by gaseous absorption or other known phenomena at the time of the experiment.

Detailed analyses of these data are presented in References 1, 2, 3, 4, and 15.

An important consequence of these measurements was the subsequent development of a model which successfully predicted both the variance and mean power behavior observed in both this experiment and other related measurements. This was achieved by accounting for both the angle of arrival fluctuation as well as the amplitude fluctuation of the received signal. This approach predicts the occurrence of gain degradation under conditions of high turbulence, electrically large apertures, and/or long path lengths. The detailed development of this theoretical treatment is presented in Ref. 14.

It must be emphasized at this point that virtually all of the data for the ATS-6 return experiment were obtained under clear sky conditions. Thus, the resulting model is applicable only to this case. The treatment of these effects in the presence of rainfall remains to be accomplished.

COMSTAR ANGLE OF ARRIVAL MEASUREMENTS

Existing theoretical models predict that angle of arrival fluctuations should be independent of frequency. Thus, the availability of the 28.56 GHz beacons on the geosynchronous Comstar satellites made it possible in 1978 to measure angle of arrival fluctuations at this frequency in order to compare the results with those obtained using the 11.7 GHz CTS beacon. This was accomplished using the CTS self phased array and receiving system described above; the antenna feeds and front-ends were simply modified for 28.56 GHz operation.

Comstar D/1 was acquired at an elevation angle of 24° on July 7, 1978, and Comstar D/2 was acquired at an elevation angle of 42° on July 12, 1978. These satellites were observed alternately until they were shut down on August 31, 1978. Since that time Comstar D/3 has been under observation at an elevation angle of 43° . Table 2 summarizes the number of hours of data recorded per month up to the time of this writing.

On September 13, 1978, the phase stability of Comstar D/3 deteriorated seriously and exhibited frequency jumps of 50 Hz or more. This behavior was similar to that experienced with CTS; in both cases the phase stability improved following eclipse periods but never returned to its original state. This behavior was confirmed by the Bell Telephone Laboratories. Subsequently, in December, 1978, the bandwidth of the receiving system was increased to accommodate this phase behavior. This increase was acceptable since the signal to noise ratio of the Comstar receiving system was considerably higher than that of the CTS system. After the modification, the signal to noise ratio was 25 dB.

The initial data analysis has indicated that an angle of arrival deviation of 0.10° is exceeded 0.01% of the time. This value compares quite well with that measured at 11.7 GHz and tends to confirm the prediction that angle of arrival fluctuation is frequency independent over this portion of the spectrum. Therefore, a 4 m parabolic antenna

TABLE 2.

<u>Month</u>	<u>Hours of Data</u>
D/1 and D/2 operations	
July, 1978	186 ¹
August	212 ²
D/3 operations	
September	398
October	385
November	557
December	456
January, 1979	479
February	568
March	581
April	570
May	585
June	524
July	536
August	668
September	419
October	586
November	553
December	400
January, 1980	456
February	<u>310³</u>
TOTAL	9,031

¹System debugging.

²Lightning transient in data system.

³Data system failure.

operating at 30 GHz would be expected to experience at least 3 dB of loss in addition to rain attenuation for 0.01% of the time.

At the present time these measurements are continuing. The first twelve months of this data set have been analyzed and the preliminary results are presented in Reference 27. Amplitude and differential phase distributions for the first year of the Comstar D/3 data are shown in Figures 5 and 6. Both the quarterly distributions and the annual distributions are presented in each case. It is interesting to note that although both the amplitude and phase show less variation during the winter quarter, the differential phase distributions are much more consistent than the amplitude distribution during the remaining seasons. The differential phase data, $\Delta\phi$, may be converted to apparent angle of arrival, α , through the relationship, $\Delta\phi = 597\alpha$. Thus, the maximum differential phase shown, 90° , is approximately equivalent to an apparent angle of arrival fluctuation of 0.15° .

GAIN DEGRADATION EXPERIMENT

The angle of arrival measurements have clearly indicated that gain degradation due to angle of arrival fluctuations can be significant for small periods of time even on high elevation angle paths, i.e., short paths within the sensible atmosphere. Although the data show a high correlation between these fluctuations and rain attenuation, the amount of loss clearly associated with rain attenuation and that associated with gain degradation cannot be ascertained. Furthermore, the ATS-6 return measurements substantiate the presence of gain degradation on long atmospheric paths in clear air but do not shed any light on the behavior of turbulence and/or gain degradation during rain fade events.

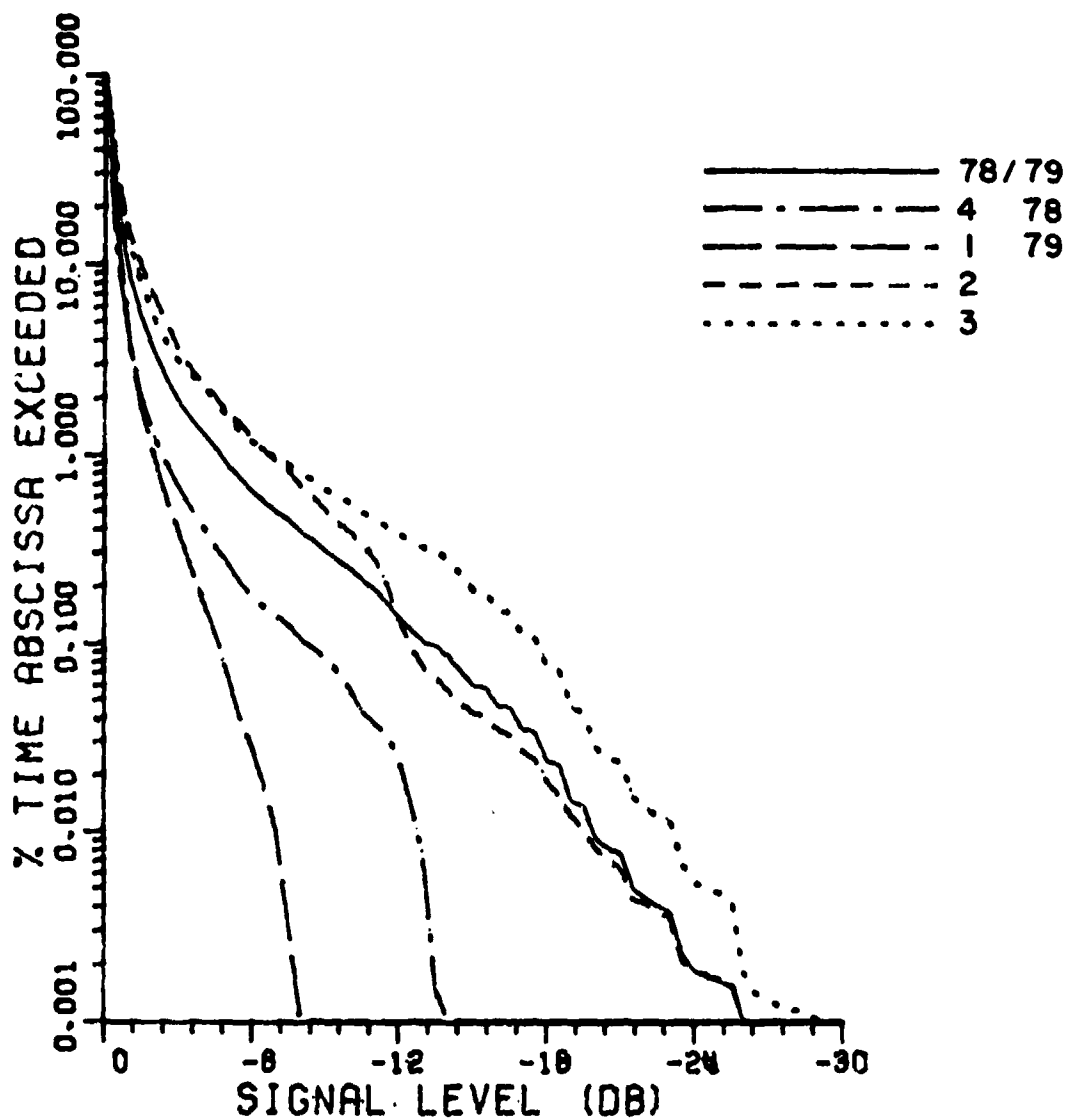


Figure 5. Quarterly and annual amplitude distributions for 12-month Comstar D/3 data period.

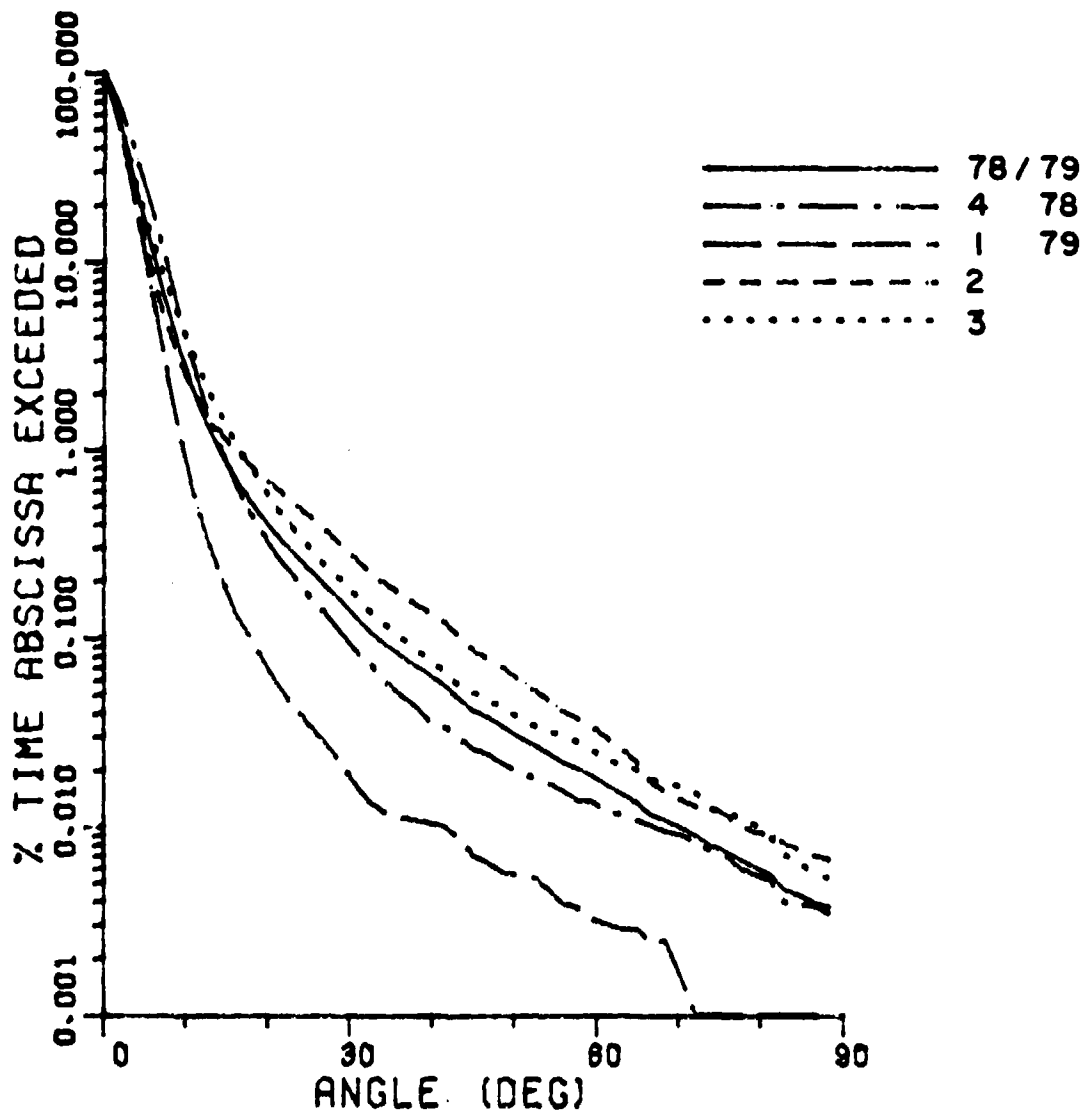


Figure 6. Quarterly and annual differential phase distributions for 12-month Comstar D/3 data period.

For these reasons a gain degradation experiment was implemented using the Comstar D/3 28.56 GHz beacon. The purpose of this experiment is the direct measurement of gain degradation by comparing the performance of large and small aperture antennas, i.e., narrow and wide beamwidth antennas.

This experiment utilizes a 5 m Cassegrainian fed parabolic antenna with a 60 cm focal point feed antenna mounted in front of the sub-reflector of the larger antenna. Thus, both antennas are aligned along exactly the same atmospheric path. The signal from the larger antenna is then padded down to equal that from the small antenna. These two signals are then alternately switched through a common receiving system in a manner similar to that used in Dicke radiometers; thus, the comparison of the two signals is independent of any drift or other change in the receiving system.

The 5 m antenna has a beamwidth of 0.16° while the small aperture has a beamwidth of 1.2° . Since both antennas are viewing the same atmospheric propagation path, both antennas will experience exactly the same attenuation due to absorption and scattering. However, the larger aperture will be much more susceptible to gain degradation due to angle of arrival fluctuation. Therefore, it is expected that the large aperture will experience somewhat larger fade depths than the small aperture. This difference is a direct measure, then, of gain degradation.

This experiment became operational in January, 1980, and is currently being used to observe rain fading on an event basis. To date no significant fades have been observed because of the winter season. However, it is anticipated that the spring and summer thunderstorm seasons will permit direct observation of the gain degradation effect. A sample of clear weather gain fluctuation is shown in Figures 7 and 8. In these figures, the lower trace shows the switch

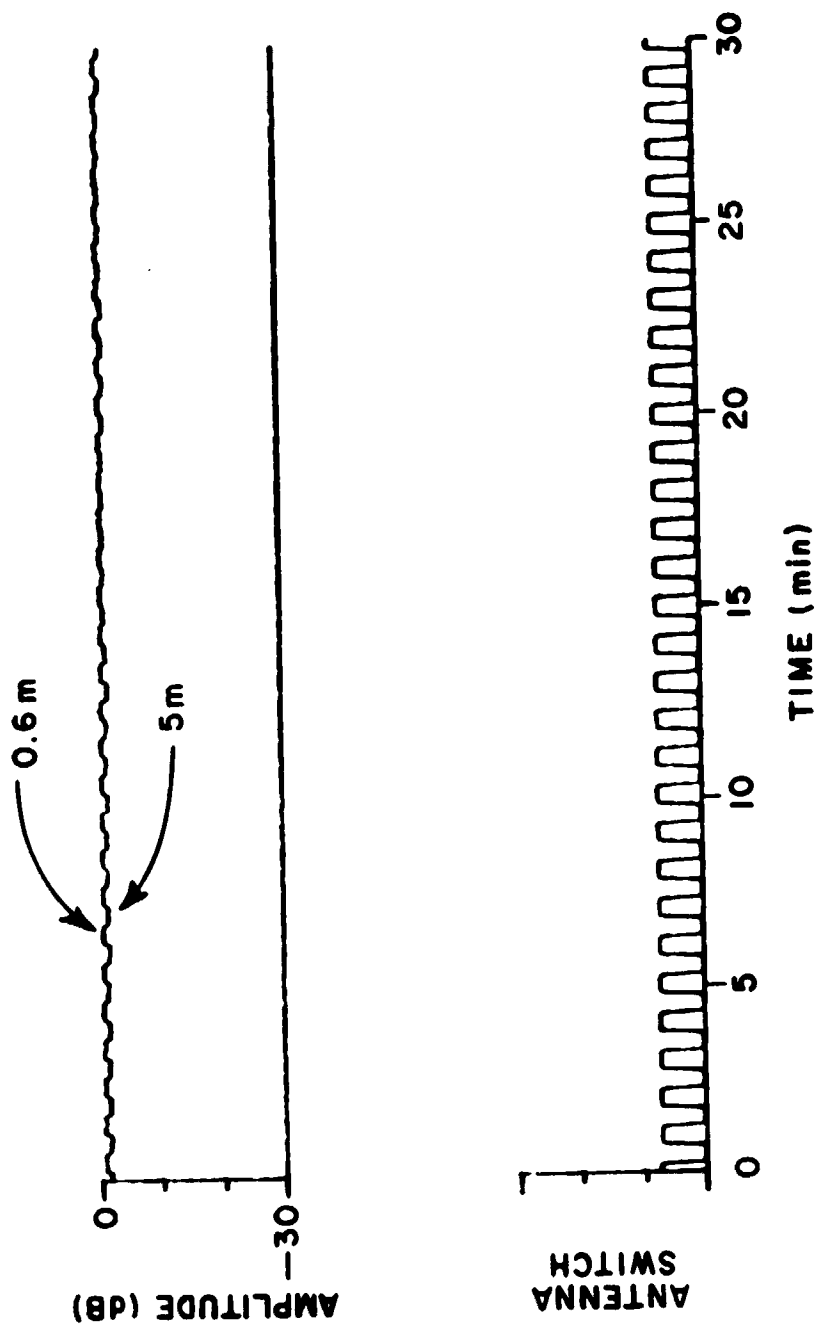


Figure 7. Gain degradation data--Day 113, Hour 15, Minute 3, Second 27, 1980.

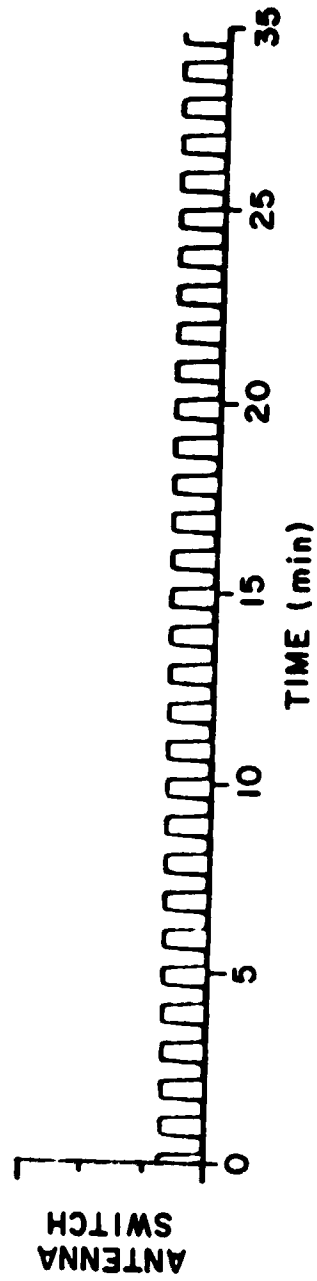
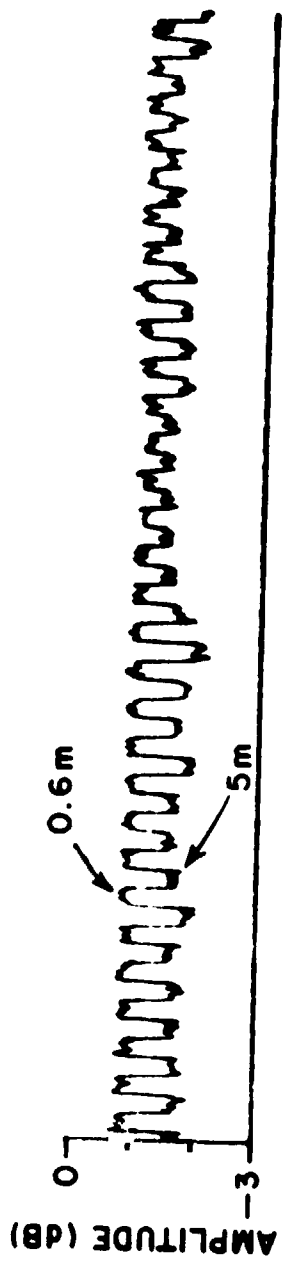


Figure 8. Gain degradation data--same as Figure 8 with expanded scale.

drive signal; when this signal is high the 5 m antenna is being monitored and when the signal is low the 0.6 m antenna is being monitored. During this particular data period the padded 5 m antenna signal is slightly lower than that of the 0.6 m antenna. In Figure 7 the received signal data are plotted on a conventional 30 dB scale and it is clear that the differential antenna gain disappears during two periods approximately 15-20 and 24-29 minutes after the start of this plot. This type of behavior is associated with the passage of small cumulus clouds through the beam. These same data are plotted in Figure 8 using an expanded 3 dB scale. Here it is quite apparent that the 5 m antenna signal (lower trace) is much noisier than that of the 0.6 m antenna although these fluctuations are still small.

RELATED TOPICS

The following summarizes related publications and activities that were a direct result of this contract effort.

References 16, 19, 21, and 23 were published in the IEEE Transactions on Antennas and Propagation and in Radio Science. These publications dealt with diversity gain, frequency scaling of rain attenuation, and the power law relationship for rain attenuation.

Invited papers were also presented on turbulence and precipitation effects at the U.S. Army Workshop on Millimeter and Submillimeter Waves⁷ and a NATO Advanced Study Institute²⁰. The latter is now available in book form as noted in Ref. 20.

Related oral presentations dealing with diversity, radar, and radiometry are identified in References 17, 18, and 22. And, related technical reports dealing with diversity, tomographic detection of rain cells, scintillation, attenuation, and dispersion are listed in References 24, 25, and 26.

This program provided support leading to the completion of two M.S. theses, D.M.J. Devasirvatham³ and R.A. Baxter¹⁵, and one Ph.D. dissertation, D.M. Theobald⁶. The program has also provided support for 5 other graduate students, in various stages of M.S. and Ph.D. programs.

SUMMARY

The research effort conducted under Contract No. NAS5-22575 has included four experimental efforts:

- 1) CTS angle of arrival measurements,
- 2) ATS-6 return measurements,
- 3) Comstar angle of arrival measurements, and
- 4) Gain degradation measurements.

The angle of arrival measurements have indicated that a portion of the fading observed during rain attenuation events may, in fact, be due to antenna gain degradation. Angle fluctuations on the order of 0.1° have been observed for periods exceeding 0.01% of the time. The latter two experiments are still underway and, thus, final results are not yet available.

Results from the ATS-6 return have permitted the development of a model which predicts clear air scintillation and gain degradation effects. This model has been found to agree with all currently available data.

The key results from these efforts have been summarized and the references containing the detailed descriptions of the experiments and their results have been given.

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